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PROBLEMS OF HEAT AND MASS TRANSFER IN A VAPOR–GAS PHASE DURING EVAPORATION OF A FLUID

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An analysis is made of the experimental data of a number of investigators on evaporation of fluid from a surface and a comparison is made with theoretical solutions and data on the injection of gas through a permeable surface.

It has been shown [1] that in the relative representation of dimensionless coefficients of heat and mass transfer as functions of permeability factors, the experimental data on evaporation from the free surface of a fluid correlate well with the corresponding theoretical solutions, particularly those based on the asymptotic laws of Kutateladze and Leont'ev [2] for a turbulent boundary layer at a permeable surface. The experimental data of a number of investigators on evaporation and injection are shown in Fig. 1 along with some theoretical solutions. Figure 1 indicates that all the data are sufficiently alike for a quasiuniform boundary layer and Le = 1 (the latter limitation is only for heat transfer) where the permeability factor B < 0.1. The coefficients of heat and mass transfer decrease as the mass flow from the surface increases, which is in accord with presently accepted views [3]. It should be noted that for evaporation it is necessary to use a Nusselt (or Stanton) number based on diffusion mass flow [4]. For evaporation of a fluid in a vapor–gas medium, it is $Nu_D W_{2i}$ ($St_D W_{2i}$).

As is clear from Fig. 1, we have the relations $Nu_D W_{2i} = Nu_{D_0}$ and $Nu = Nu_0$ when $B < 0.1$, i.e., a similarity is observed between jointly occurring processes of heat and mass transfer at low intensity and heat transfer without mass transfer. Here Nu_{D_0} and Nu_0 are the diffusion and thermal Nusselt numbers defined by the usual similarity equations such as $Nu_{(D)0} = f(Re, Pr_{(D)}, Ar)$ for separately occurring processes of mass transfer at low intensity and heat transfer without mass transfer. Experimental data confirming this hypothesis are presented in [5, 6]. However, several authors have expressed the opinion that the analogy between heat and mass transfer can break down during evaporation even at low intensity. In this regard, references are made to the experimental studies of Nesterenko [7], who was one of the first to perform sufficiently accurate measurements of temperature and concentration within a boundary layer. However, if one considers the original data of Nesterenko, breakdown

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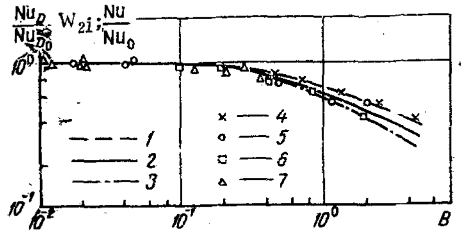

Fig. 1. Comparison of theoretical and experimental results: 1) Spalding–Mickley equation [10]; 2) Kutateladze–Leont'ev equation for a turbulent boundary layer [2]; 3) equation for a laminar boundary layer [11]; 4) uniform turbulent boundary layer on a permeable plate, heat transfer by injection [12]; 5) evaporation of a film inside a vertical tube [13]; 6) evaporation from surface of fluid [14]; 7) evaporation during transverse flow around a cylinder [1].

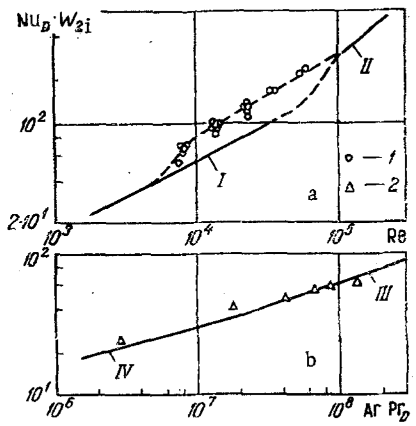

Fig. 2

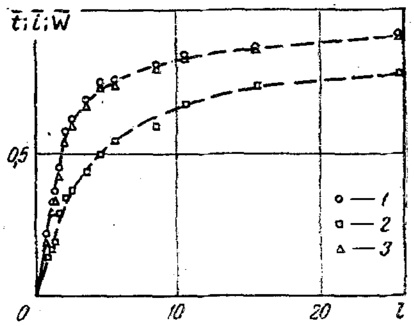

Fig. 3

Fig. 2. Mass transfer (a) for forced longitudinal flow around a flat surface and (b) for free convection: I) for a laminar boundary layer ($Nu_D W_{2i} = 0.664 Pr_D^{0.33} \cdot Re^{0.5}$, $Pr_D = 0.6$); II) for a turbulent boundary layer ($Nu_D W_{2i} = 0.036 Pr_D^{0.4} Re^{0.8}$, $Pr_D = 0.6$); III) $Nu_D W_{2i} = 0.135(ArPr_D)^{1/3}$, $ArPr_D > 2 \cdot 10^7$; IV) $Nu_D W_{2i} = 0.54 \cdot (ArPr_D)^{1/4}$, $500 < ArPr_D < 2 \cdot 10^7$; dashed curve is boundary of transition region (upper curve corresponds to low flow rates, $u_0 < 10$ m/sec) according to data of [15]; 1) experimental data of Nesterenko for evaporation of water from a flat surface and forced air flow ($u_0 = 0.6$–4.1 m/sec); 2) experimental data of Nesterenko for evaporation of water from a flat surface and free air flow.

Fig. 3. Enthalpy, temperature, and relative mass concentration fields: 1) $\bar{i}$; 2) $\bar{t}$; 3) $\bar{W}$; l, distance from evaporative surface, mm.

of the analogy does not follow if one takes into account modern advances in the theory of heat and mass transfer. The values of the diffusion Nusselt numbers ($Nu_D W_{2i}$) obtained by Nesterenko do not exceed the corresponding values determined from the formulas for ordinary heat transfer without mass transfer for the conditions of free convection and forced flow around a plate; as is clear from Fig. 2a,b, they are in completely satisfactory agreement with the relationships for those cases known from the handbooks. It should be noted that the experimental data of Nesterenko are presented here in the form of the diffusion component of the mass flow, $Nu_D W_{2i}$. As is clear from Fig. 2a, introduction of the Guchmann number is not required for the analysis of these experimental data. An evaluation of the data obtained by the author for heat transfer is not made here, since determination of the heat load during nonadiabatic evaporation was made by subtraction from the total heat load of the radiative component of heat transfer, which in absolute magnitude is of the same order of magnitude (slightly greater) as the convective component, with possible significant error resulting.

Berman [8] pointed out earlier the agreement of the relations obtained by Nesterenko for the diffusion number Nu_D with existing relations in the literature for heat transfer without mass transfer.

On the basis of measured laminar temperatures and concentrations (from the temperatures of wet and dry thermocouples), Nesterenko concluded that in nonadiabatic evaporation, similarity of the temperature and concentration fields above the surface of evaporation is absent and, consequently, the analogy between the processes of heat and mass transfer during their joint occurrence is not observed.

However, similarity of the velocity, relative mass concentration, and enthalpy fields occurs [2] when $Pr = Pr_D = 1$, $dp/dx = 0$, and for similar boundary conditions as follows from the equations for transfer of momentum, mass, and heat. A representation of the experimental data of Nesterenko for the case of nonadiabatic evaporation (see Fig. 3) indicates the existence of a similarity between the relative mass concentration and enthalpy fields. We point out that an analogous result was obtained for evaporation and condensation (of water) in a slot by Leont'ev and Khamadov [9], who made measurements of the temperature and concentration fields by means of dry and wet thermocouples.

Nesterenko obtained totally satisfactory similarity of concentration and temperature fields for adiabatic evaporation. In this case, the parameters of the moist air in a transverse section of the flow (flow–wall) varied along the line t_M = const, and from the I–D diagram there should be similarity of temperature, enthalpy, and concentration for all points on the line t_M = const. From the similarity in the distributions of enthalpy and relative mass concentration (for Le = 1), there follows the equality of the diffusion and thermal Nusselt numbers, $Nu_D W_{2i} = Nu$, for jointly occurring heat and mass transfer.

Consequently, the experimental data of Nesterenko and other authors for $B < 0.1$ confirm the existence of similarity in the relative mass concentration and enthalpy fields for adiabatic and nonadiabatic evaporation and reveal no increase in the intensity of heat transfer and mass transfer in this region.

NOTATION

$B = (W_{1i} - W_{1o})/(1 - W_{1i})$, generalized mass content; W, mass content of a component in the vapor–gas phase; t_M, wet-bulb temperature; $\bar{t} = (t_i - t)/(t_i - t_o)$, $\bar{i} = (i_i - i)/(i_i - i_o)$ $\bar{W} = (W_1 i - W_1)/(W_1 i - W_{1o})$, dimensionless temperature, enthalpy, and relative mass concentration; $Nu = \alpha l/\lambda$; $Nu_D = \beta l/D$; $Re = u_o l/\nu$; $Le = D/a$; $Ar = gl^3\Delta\rho/\nu^2\rho$. Indices: 1, vapor; 2, gas; i, interface; 0, outside boundary layer.

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